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Messinian erosional and salinity crises: View from the Provence Basin (Gulf of Lions, Western Mediterranean)

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Abstract:

Though the late Miocene "Messinian Salinity Crisis" has been intensely researched along the circum-Mediterranean basins, few studies have focused on the central part of the Mediterranean Basin and, especially, the pre-salt deposits. To improve our knowledge of the Messinian events, it is imperative to better understand this domain. In this study, we provide a more complete understanding of this central domain in the Provence Basin. We were able to recognize: a) thick marine detrital series (up to 1000 m) derived from the Messinian subaerial erosion which is partly prolongated in the distal part by b) a thick unit of deep marine deposits (up to 800 m) prior to the evaporites; c) a thick presumed alternation of detritals and evaporites (1500 m) below the mobile halite; and d) a two-step transgression at the end of the Messinian. Spatially, we document the eroded shelf to the deep basin (and from the western to the eastern parts of the Gulf of Lions), and temporally, we extend the interpretations from the early deposition of detritic sediments to the final sea-level rise. The results provide a new basis for discussion not only for the development of the Messinian Salinity Crisis but also for the reconstruction of the subsidence history of the Provence Basin.

Keywords: Messinian; Salinity Crisis; Gulf of Lions; Mediterranean; Provence Basin; Miocene; detrital deposits; erosion

2 Introduction

The reduced inflow of Atlantic Ocean water through the Betic and Rifian corridors (Fig. 1) at the end of the Miocene, together with a high evaporation rate, led to a significant lowering of the Mediterranean Sea's base level and gave rise to one of the most prominent episodes of the Sea's history, known as the “Messinian Salinity Crisis”. This Salinity Crisis continues to raise questions and arouse interest. First, because of the wide geographical extent of the extreme environment, the Messinian gave rise to one of the largest evaporite basins known (2.5 millions km^2), comparable in size to the North Sea Permian basins (Ziegler, 1982). Its comparatively younger (Neogene) age also makes it much more accessible to analysis and modelling than older and deeper large known basins. Second, the volume of the Messinian evaporite series is greater than 1 millions km^3 in the Mediterranean Basin (Ryan, 1973). The Messinian (evaporitic and erosional) events are also distinctive in that they occurred in a relatively brief period of ~ 0.63 My (Hilgen et al., 2007) and during the history of an oceanic-type basin which is at least 15 millions years old.

A supply of oceanic water to the basin is necessary to explain the thickness of the evaporite layer. In view of the absence of connections with the Indian Ocean, the history of the eastern Mediterranian Basins (e.g. Tyrrhenian, Ionian) is linked intimately to the western basin. Within the western Mediterranean Sea, the Gulf of Lions is exceptional in that its sedimentary strata have not been deformed. In addition, the Gulf of Lions is characterized by relatively constant subsidence with continuous accommodation space for sediment accumulation. This margin is also characterized by a gentle slope, which prevents major remobilization and gravitational movements. This configuration, together with the availability of a vast data base, enables us to describe full geometries of the stratal patterns of Miocene series (from the intensely eroded geomorphologies on the shelf to the well preserved successions in the basin).

Previous studies have focused on “marginal” or “peripheral” basins (mainly present-day onshore areas) rather than on the “central” basins (present-day offshore areas). The central basins are relatively of wide extent and contain thick evaporitic sequences, while marginal basins are much smaller with reduced evaporitic sequences (Fig. 1). These basins have also been studied with two very different approaches due to their accessibility: outcrop studies, and some mines and boreholes in marginal basins and remote geophysical techniques in the central basins. So far the central Mediterranean Basin has been poorly known, due to its relative inaccessibility and lack of integration of available data.

3 Overview of previous works

Pioneer works based on field studies described a huge incision in the Rhône River valley at the end of Miocene (Fontannes, 1882; Depéret, 1890, 1893; Denizot, 1952). The isolation of the Mediterranean at that time, a drop in sea level, the subsequent invasion of the sea in the fluvial network in earliest Pliocene and the idea that a salinity crisis could have occurred were proposed very early (Denizot, 1952; Ruggieri, 1967). The development of reflection profiling techniques and increasing exploration established the existence of a mobile layer capable of generating diapirs beneath the floor of most of the central basins of the Mediterranean Sea (Alinat and Cousteau, 1962; Hersey, 1965; Menard et al., 1965; Glangeaud et al., 1966; Ryan et al., 1966; Leenhardt, 1968; Mauffret, 1970; Montadert et al., 1970; Auzende et al., 1971; Ryan et al., 1971). The origin of this layer was largely interpreted as related to salt deposition. However, different interpretations were proposed for the age of salt deposition and its disposition (Glangeaud et al., 1966; Cornet, 1968; Ryan, 1969; Mauffret, 1970; Montadert et al., 1970). Using new and high quality seismic data acquired in the Mediterranean Basin in 1970, Auzende et al. (1971) proposed that the salt was late Miocene in age, following earlier suggestions from Denizot (1952) and Ruggieri (1967). At the same time, the salt was cored during Leg 13 of the Deep Sea Drilling Project in 1970 along with its cover of gypsum, anhydrite, lacustrine mud and marls with clastics reworked from the margin. This layer was dubbed the “Upper Evaporites” by the Leg scientists. All these deposits were indisputably dated and interpreted for the first time as deep-basin products of the Messinian Salinity Crisis (Ryan et al., 1970; Hsü, 1972b; Hsü et al., 1973b). Two models, both based on the deposition of evaporites in shallow water depth were proposed and initiated a heated debate in the scientific community: the “shallow water, shallow-basin desiccation model” (Nesteroff, 1973); and the “desiccated, deep basin model” (Hsü, 1972b; Cita, 1973; Cita and Ryan, 1973; Hsü, 1973; Hsü et al., 1973a; Ryan, 1973).

The first model suggests the existence of a shallow basin (several hundred meters deep) before the Salinity Crisis. This model envisioned vertical tectonic movement during the Pliocene that would have deepened the basin after the crisis (Bourcart, 1962; Pautot, 1970; Auzende et al., 1971; Burollet and Byramjee, 1974; Stanley et al., 1974; Rouchy, 1980, 1982). But considering that different basins that make up the Mediterranean are of different ages —some much older (such as the Ionian Sea), others much younger (such as the Tyrrhenian Sea) — this Alpine tectonic model soon became obsolete. The second model suggests the existence of a deep basin (over 1500 meters deep) before the Messinian crisis (Argand, 1924; Cita, 1973; Hsü, 1973; Hsü et al., 1973b; Hsü and Bernoulli, 1978; Montadert et al., 1978; Stampfli and Höcker, 1989) and a sea-level drop of around 1500 m. Three arguments were used to strengthen this theory: the tidal nature of the evaporites recovered in all the major basins (Hsü, 1972a, 1972b); the pan-Mediterranean distribution of seismic reflector M, that was calibrated with the abrupt contact between the evaporites and the overlying Early Pliocene marls (Ryan, 1973), and the open marine, deep bathyal nature of the pelagic sediments immediately superposed on the evaporites (Cita, 1973).

The deep basin model could also be defended by kinematic and geodynamic considerations: such a basin, opened by the rotation of a microcontinent during the Oligocene time (at around 30 My) in the general framework of African-European convergence (Smith, 1971; Dewey et al., 1973) can at the time of the Messinian only have been deep. A final decisive argument in favour of this spectacular hypothesis came from studies on the marginal erosion coeval with the central basin evaporites all around the Mediterranean (Barr and Walker, 1973; Chumakov, 1973; Clauzon, 1973, 1974; Cita and Ryan, 1978; Clauzon, 1978; Rizzini et al., 1978; Ryan and Cita, 1978; Clauzon, 1979; Barber, 1981; Clauzon, 1982). The convergence of observations has made it possible to exclude regional tectonic factors and confirm that the eustatic fall of more than 1500 m sculpted the Mediterranean river systems during the Messinian Crisis. This result was obtained mainly from onshore observations but it has also been supported by seismic reflection surveys over a width of some hundred kilometres on the Gulf of Lions shelf (Burollet and Dufaure, 1972; Biju-Duval et al., 1974; Burollet and Byramjee, 1974; Gennesseaux and Lefebvre, 1980; Lefebvre, 1980). The "Desiccated, deep basin model" (Hsü, 1972b; Cita, 1973; Hsü, 1973; Hsü et al., 1973a) was therefore widely accepted at that time. Some years later, Gorini (1993) and Guennoc et al (2000) compiled a map of the subaerial erosion surface over some 15,000 km² in the shelf of the Gulf of Lions. This confirmed, over a distance of some 100 km, the existence of a major Languedocian paleoriver. In the eastern part of the shelf they also mapped the channel of a paleo-Rhône (Fig. 1). These observations although likely to provide us information on the paleoshorelines of the Messinian basin, were, unfortunately only mapped down to the upper continental slope.

Messinian evaporites have been described as three different sub-units from the top to the base: 1) The "Upper Evaporites" sequence with high amplitude reflectors (M reflectors) at its top, it has only been sampled in its upper part in the deep basin (Ryan et al., 1973); 2) The massive salt layer which has never been cored, its limits have long been recognized thanks to seismic interpretations (Mauffret et al., 1973; Ryan, 1976); 3) A lower unit with high amplitude, well stratified reflections was first interpreted as a velocity artefact and then named "Lower Evaporites" using a simple analogy with the two evaporitic units observed in Sicily which are accessible for outcrop studies (Decima and Wezel, 1971). A thickness on the order of 500 m has been proposed (Montadert et al., 1978).

Some major questions remain concerning the beginning of the crisis in the central Mediterranean Basin. The geometric physical link between the evaporitic series identified in marginal basins accessible for field studies and the evaporitic series of the central basins has never been made. The many interpretations concerning the marginal and central Messinian deposits are well summarized in a review article by Rouchy and Caruso (2006). Two major groupings are evident: one that favours a synchronous deposition of the first evaporites in all the basins before the major phase of erosion (Krijgsman et al., 1999); and the other that favours a diachronous deposition of the evaporites through more than one phases of desiccation which would first have affected the marginal basins and later the central basins (Clauzon et al., 1996; Riding et al., 1998; Butler et al., 1999). In spite of conflicting interpretations, most workers agree with a three-phase progression: 1) a period of partial confinement leading to a limited regression (onset of evaporite deposition in the marginal basins at 5.96 Ma (Gautier et al., 1994; Krijgsman et al., 1999; Sierro et al., 1999); 2) a period of near desiccation (major regression); 3) followed by the Pliocene reflooding. Estimates differ on the age and duration of phase 2: beginning at 5.6 Ma (Clauzon et al., 1996; Krijgsman et al., 1999; Rouchy and Caruso, 2006), or slightly earlier (Butler et al., 1999). The reflooding of the Mediterranean Basin is considered to have been sudden during the earliest Pliocene (Hsü et al., 1973a; Clauzon and Cravatte, 1985; Pierre et al., 1998; Blanc, 2002; Lofi et al., 2005) and a precise age has been proposed at 5.33 Ma (Hilgen and Langereis, 1993; Van Couvering et al., 2000; Lourens et al., 2004).

Surprisingly, detritic deposits in the Gulf of Lions that must have originated during the huge erosional event were not described until 2002. Savoye and Piper (1991) identified some deposits in the Var region, but Lofi (2002) first identified detrital sediments in the Provence Basin at the outlet of the Languedoc paleoriver. The small volume of the detrital products (1500 km^3) compared to the high volume of estimated erosional sediments (3000 km^3) was explained by the deposition of a part of detritus in the basin (intercalated with gypsum and anhydrite in the "Lower Evaporites" below the salt) (Lofi et al., 2005). Recently, Lofi and Berné (2008) described pre-Messinian submarine paleo-canyons just below the detritals. We will refer to this proposition later in the Discussion Section. Sage et al. (2005) and Maillard et al. (2006) have also described detritals on the Sardinian and Valencia margins.

4 Data and method

One of the major assets of this study has been the large amount of data collected in the area for both industrial and academic purposes. A partnership with Total gave us access to an exceptional set of conventional and high-resolution seismic reflection data from the coast to the deep domain (Fig. 2). Seismic interpretations have been performed using the principles of seismic stratigraphy (Vail et al., 1977). We identified seismic units based on stratal terminations and configurations of seismic reflections. The large coverage of seismic data enabled us to map the units in 3D throughout the Gulf of Lions from Cap Creus to Provence and from the present day coast to the basin area (~ 2500 m water depth).

Additional data were obtained from the e-logs of nine industrial boreholes that sampled the sedimentary cover down to the substratum (Fig. 2). A detailed micropaleontological study (Cravatte et al., 1974) provided information on the biostratigraphy and depositional environments of the Miocene, Pliocene and Quaternary successions in four of the wells (Mistral1, Sirocco1, Autan1 and Tramontane1). The data from these wells were synthesized in a compilation of all the drilling reports (Guennoc et al., 2000).

The Ecors programme (De Voogd et al., 1991) provided three general seismic sections across the entire margin, completed by a series of ESP (Expanding Spread Profiles) (Pascal et al., 1993). ESP data and average velocities in wells were used to obtain propagation velocities from which it was possible to estimate the thickness of the series from the seismic data (time-depth conversion), thus giving access to volume estimates of the units involved.

5 Results: from the eroded Gulf of Lions shelf and slope domain to the evaporite domain

Here, we will describe the depositional geometries of the Gulf of Lions from its eroded margin to the evaporite domain. Although these two domains have been known for many years, they were studied separately and the direct geometrical link between them was not established for all of the sedimentary series. We categorize three characteristic domains from the shoreline to the centre of the basin (Figs. 3 and 4):

- The eroded domain, characterized by a single discordant surface between the Miocene deposits and the Plio-Pleistocene deposits (without any Messinian deposits).
- A complex intermediate domain, at the bottom of the continental slope, corresponding to the area in which the Messinian erosion products were deposited (Lofi et al., 2005).
- The evaporite domain characterized by a continuity of the succession throughout the Messinian period and by the presence of evaporites.

5.1 The eroded domain

A pervasive erosional surface (dark blue lines on Fig. 3) has long been identified in the Rhône Valley (Denizot, 1952; Clauzon, 1973, 1982) and on the Gulf of Lions shelf where it is very clearly discernable in the seismic reflection profiles (Ryan and Cita, 1978; Gennesseaux and Lefebvre, 1980; Lefebvre, 1980; Gorini, 1993; Guennoc et al., 2000; Lofi, 2002; Lofi et al., 2005). This erosion surface, i.e. the discordant contact between the Miocene deposits and the overlying prograding Plio-Pleistocene sequence beneath the shelf and slope, was named "Margin Erosion Surface" (MES) by Lofi et al. (2005) and Lofi and Berné (2008).

5.1.1 The Miocene eroded series

The cross sections in Figure 3 (c, d, e) show that a large part of the Gulf of Lions is buried beneath a pre-Messinian sedimentary cover. Reflections are planar and parallel and show good continuity with few thickness variations. Landward, in the direction of Provence and the Pyrenees, the reflections terminate as onlaps on rises of pre-rift substratum (Fig. 3d); basinward, they prograde or lap out approximately up to the present-day slope (Fig. 3c). The pre-Messinian succession is eroded and slightly deformed, except close to the Pyrenees in the West where faults and roll-over tilting are observed (Mauffret et al., 2001; Lofi et al., 2005). Boreholes show that the erosion surface of the shelf truncates sediments of the Miocene age and is covered by sediments of the earliest stage of the Pliocene (Cravatte et al., 1974). Up to 7 My of the Upper Miocene sediment record are missing in Autan borehole at the shelf edge where youngest deposits are dated at ~12 My (post last occurrence of *Globorotalia peripheroronda*), having been removed by erosion during the Messinian Salinity Crisis. However, the youngest Miocene sediments were found in the Tramontane well and were dated as Tortonian (Cravatte et al., 1974). In the Cicindelle borehole we found that the entire Miocene was removed so that the Pliocene lies directly on the substratum (Fig. 3d). The Gulf of Lions can be sub-divided into two main areas (Fig. 3d): a Languedoc area in the southwest where substratum was highly subsident so that an accommodation of 2000 to 3000 m was available for the Miocene sediments, and a Provence area where the substratum is in a much higher position and lack of accommodation prevented deposition and/or preservation of thick Miocene strata. It is also deeply incised.

5.1.2 Morphology of the Margin Erosion Surface

A large part of the MES had already been mapped and interpreted in the past. The mapping revealed a pattern of up to 5th order dendritic drainage (Gennesseaux and Lefebvre, 1980; Gorini et al., 1993; Guennoc et al., 2000; Gorini et al., 2005; Lofi et al., 2005) with two main systems (Fig. 4). One to the East, corresponding to the Rhône (which was located East of present day Rhône River) together with a network from the region of Montpellier, both join up downstream into a single valley. The other to the West, with headwards extending from the Languedoc and Roussillon region. The Rhône largely incised the Mesozoic limestone substratum, whereas the Languedoc cuts mainly into the Miocene marls. In both cases, several hundred metres depth can be observed between the thalweg and the interfluves. This height however does not represent the total amount of erosion by the rivers, as interfluves themselves are eroded, so the total amount of erosion could be much greater (see next section).

The drainage networks (MES) have sculpted a “rough” or “badland” morphology (Ryan, 1978). In this study we also observed that this morphology gives way basinward to a planar and “smooth” surface that is locally conformable with the underlying Miocene series but that is also locally erosional as it truncates the underlying succession of the intermediate domain (unit Dm on Fig. 3). This smooth surface slightly deepens seaward and extends over 60-70 km. The transition between the two morphologies (rough and smooth) is very clear and lies at a constant two-way traveltime depth of 1.6 seconds over most of the shelf (Fig. 6), albeit slightly less at the edges of the basin (1.4 seconds two-way traveltime in Provence and Catalonia). An interpretation of this change in morphology will be proposed later in the Discussion Section.

5.1.3 Volume eroded by the Margin Erosion Surface

It is possible to obtain a minimum volumetric estimate of the Miocene sediments that have been removed by erosion in the western part of the Gulf of Lions. Figure 7 shows the measurement method and the estimated values. The Miocene deposits, wherever they are observed, are extremely regular over a large part of the continental shelf and the first signs of a progradation only occur at approximately 90 km from the coast (Fig. 3c). Consequently, up to this point, one can simply extrapolate the intervals removed by erosion. This technique was used earlier by Mauffret et al. (2001) and Lofi et al. (2005) but only in the Languedoc and Roussillon areas which led to a minimum estimate of about 3000 km^3 of eroded sediments. An average velocity of 2000 m/s (Lofi et al., 2005) was used for the evaluation of thicknesses within the Miocene and Messinian series. Here, we extended this technique to the East, to the Rhône area as far as the regional reference marker exists. Figure 7a gives a perspective view of three selected profile segments from the seismic coverage. LRM 08 on Figure 7 intersects the Miocene succession where it is best preserved. We extended the youngest observed horizon (Late Miocene) parallel to a regional marker horizon preserved within the series over the entire area. The minimum eroded thickness through extrapolation is shown in yellow on Figure 7. This new evaluation provides an estimated volume of 4000 km^3 of eroded sediments (Fig. 7b). Note that this amount of sediments does not take into account the entire eroded area. If we consider the whole Rhône Valley and shelf of the Gulf of Lions where the erosion surface has been observed (> 20 000 Km^2), we can assume the eroded volume to be much higher (~10 000 Km^3). Note also that this volume does not take into account the direct input from the Rhône River. This volume of eroded sediment must have been transported downstream and deposited into the deep basin.

5.2 <u>The intermediate domain (between the eroded shelf and the evaporite domain)</u>

The intermediate domain is characterized by a seismic unit (unit Dm) sandwitched between the prograding Miocene deposits below and the Pliocene deposits above and bounded both at its base and top by discontinuities (Figs. 3a, b, c and e). One thus passes from an eroded domain, characterized by a single “rough” (MES) then “smooth” erosion surface occurring between Miocene and Pliocene sediments, to a more complex, intermediate domain where the Miocene and Pliocene sediments are separated by the unit Dm.

5.2.1 Description of unit D-geometries

The edge of the Miocene shelf is truncated by a surface inclined (~2.5°) towards the basin (surface in red in Figures 3a, b, c, e). This surface characterizes the base of unit Dm that shows a major incision (up to 1500 m) at the outlets of the Rhône and of the Pyrenees-Languedoc drainage networks (Fig. 5). The incision is less marked between these two areas. Three subunits can be recognized in unit D whose extension has been mapped (Figs. 3 and 4).

- Subunit Dm0 is the lower member of unit Dm and can be seen at the outlet of the Rhône. It is characterized by clinoforms that dip steeply basinward and extend deep beneath the salt. The clinoforms are up to 1 km in height, they are truncated upstream by the smoother surface described earlier (Fig. 3a, b).
- Subunit Dm1, lying unconformably on subunit Dm0, is present over the entire margin at the outlet of the Roussillon-Languedoc valleys and the Rhône valleys one. Like subunit Dm0, it is characterized by basinward dipping clinoforms (also up to 1 km in height) and also truncated upstream. Basinward, down-dip from the strata, we observe two distinct seismic facies (Fig. 3e): a chaotic facies located mainly on the outlet of the erosional valleys (on the western side); and a facies characterized by more or less continuous reflections (on the eastern side). This facies difference is probably due to whether or not the area had a direct connection with the drainage systems. On Figure 4 we can see rises of the substratum that most likely isolated the eastern side from a direct input of the Rhône and Languedoc sediments, so that sediments are more homogenous and probably more shalier. In both cases, the upper part of subunit Dm1 extends beneath the salt and becomes imbricated in a continuous high-amplitude reflector (LU1) present in the evaporite domain.

- The upper subunit, Dm2, is characterized by a chaotic high-amplitude seismic facies (called “CU” in Lofi et al., 2005) located at the immediate outlet of the Languedoc drainage network. A direct connection with the Rhône system and a deposition of coarse deposits can be assumed. This subunit is also truncated in its upstream part. The base of subunit Dm2 ties in basinward with the base of the mobile salt unit (MU).

5.2.2 Description of unit D in the boreholes

Two boreholes cross the unit Dm (Fig. 4). Autan1 is localized on the edge of shelf and GLP2 on the slope, at the limit of the salt deposit.

- Autan1 (Cravatte et al., 1974) indicates, for the interval corresponding to the unit Dm (2424-2997 m), sandy carbonated clay with rare foraminiferas which are often broken and of small size. The lack of significant planktonic foraminiferas prevents precise dating for this interval, however an Upper to Middle Miocene age with marine environment is suggested (Cravatte et al., 1974). A gap of Messinian and Tortonian is also assumed. Cravatte et al. (1974) added that the cuttings of drilling are often not representative because of the significant contamination and the conditions of drilling. The only representative samples are the slabs (one side core drillings) but they were few in number.
- GLP2 presents many reworkings at all levels of the borehole which made interpretation very tricky (Brun et al., 1984). Under salt and anhydrite deposits related to Messinian, carbonated clays (sometimes with silt) are described. This interval, corresponding to unit Dm (3703-4856 m), provides limited information. An uncertain Burdigalian to Tortonian age is suggested.

Autan1 and GLP2 boreholes therefore provide poor fossil associations for the interval corresponding to the unit Dm. On top of that, reworkings described in GLP2 and Autan1 (broken forams) lead us to remain cautious on ages (undifferentiated Burdigalian to

Tortonian, see 5.2.2). Samples in regressive seals, which are made of reworked and mixed material are known to be poor intervals for age credibility (B. Haq, personal communication). Both ages given by these two boreholes are doubtful, and have not been used by us. A Messinian age for the deposits (reworking previous sediments) can not be rejected.

5.2.3 Volume of Unit Dm

Figure 8 shows the isopach map of Unit Dm. The maximum observed thickness is more than 1000 m, with the depocentre located downstream of the outlet of the Roussillon-Languedoc rivers and the Rhône River. The corresponding volume can be estimated at ~4700 km^3 if we consider the average velocity of 2000 m/s used by Lofi et al. (2005). In fact, a velocity of 3000-4000 m/s is probably more appropriate (Fahlquist and Hersey, 1969; Leenhardt, 1970), so that the volume of unit Dm could even reach values of 9400 km^3. This does not include the most distal deposits located in the very deep basin area nor the lateral equivalent of the shelf-edge prisms Dm0, Dm1, Dm2 towards the East.

5.3 The evaporite domain

Directly below the Pliocene and Quaternary sediments (Fig. 3c, f), the upstream extension of the “Upper Evaporites” is marked by onlaps onto the top of unit Dm. These “Upper Evaporites” made-up of intercalated beds of anhydrite and clay (Ryan et al., 1973) and also named “Upper Unit” (Lofi and Berné, 2008), have been deformed by creeping and sliding of the underlying salt and by listric faults.

The massive salt underlying the “Upper Evaporites” is the most representative facies of the Messinian in the basin. It is characterized by a transparent seismic facies forming salt domes, formed as the salt flows since the early Pliocene and during the deposition of the Pliocene and Quaternary turbidites (Dos Reis et al., 2005). Its original upstream extension (before movement) can be considered as the limit between the listric faults (which sole out at the base of the salt) and subunit Dm2 (see on Figure 3). This unit is named the "Mobile Unit" (MU) by Lofi et al. (2005).

Below the mobile salt (MU) we found a unit characterized by continuous parallel high-amplitude reflections (LU1). The upper part of this unit was described and interpreted as "Lower Evaporites" by analogy to the seismic facies of the "Upper Evaporites" and by analogy to the evaporite trilogy in Sicily (Montadert et al., 1978). The reflections clearly onlap the lower part of unit Dm (Dm0 and Dm1, Fig. 3c). The facies is thick in the basin (it reaches 0.6 seconds two-way traveltime) and thins over unit Dm in the intermediate domain. The upper part of LU1 is imbricated with the upper part of subunit Dm1 (lateral facies transition).

Beneath the LU1 unit, we found a facies with average-amplitude reflections that are more or less continuous. This facies (LU0) is the lateral distal equivalent of the lower part of Unit Dm (subunits Dm0 and Dm1). The base of this distal unit is marked by a high-amplitude reflector that becomes erosive toward the intermediate domain and which corresponds to the base of unit Dm. The lowermost sediments (below LU0) rest directly on the basement and represent the deep deposits of the Miocene post-rift margin.

To summarize, we have described and correlated three major seismic domains. The first is characterized by intense erosion (MES), the second by deposition at the outlet of the river valleys (unit Dm), and the third by an evaporitic deposition. It should be noted that the base of unit Dm, characterized by major erosion in the intermediate domain, extends conformably and widely into the basin below LU0 unit (Fig. 3c).

6 Discussion

The results that we discuss here include the recognition of thick marine detritic deposits that provides the evidence of a huge detritic phase prior to the evaporite deposition in the central basins; the presence of presumed evaporites, with a thickness of up to 1500 m, located below the thick halite; and finally the evidence of a two-step transgression at the end of the Messinian.

6.1 The detrital succession derived from Messinian subaerial erosion

The analysis of depositional geometries provides evidences of a huge phase of subaerial erosion in the Rhône Valley and on the continental shelf of the Gulf of Lions (MES). A major drawdown was thus necessary to deeply incise these domains and particularly the Miocene shelf. We assume that only the major Messinian drawdown was able to produce this huge phase of erosion. This major drawdown (~ 1500 m) has been strongly argued in the past (Ryan and Cita, 1978; Gennesseaux and Lefebvre, 1980; Lefebvre, 1980; Clauzon, 1982; Gorini, 1993; Guennoc et al., 2000; Lofi, 2002; Gorini et al., 2005; Lofi et al., 2005). This estimate mainly results from observations done during dives realized by Savoye and Piper (Savoye and Piper, 1991) and is now largely accepted as shown by the recent published "Consensus" about the MSC scenario (CIESM, 2008). However, no evidence had been produced of corresponding detrital deposits before 2002. Several studies have since proved (Lofi et al., 2005; Sage et al., 2005; Maillard et al., 2006) its existence between the evaporite domain and the foot of the continental slope. Nevertheless, the limit of its lower boundary (due to lack of seismic penetration) or its lateral correlation to the deep basin succession (due to the lack of lateral seismic data) have remained undetermined.

Unit Dm that we described is sandwitched between the Miocene shelf deposits and the Pliocene and Quaternary cover (Fig. 3). A major unconformity characterizes the base of unit Dm and other minor surfaces can also be observed within this unit (Fig. 3e). Two conflicting interpretations (depending on the position of the "Basal Erosion Surface" (Maillard et al., 2006), i.e., the discordant contact between the pre-salinity crisis deposits and the syn-crisis deposits) can be proposed and will be discussed here about the age of unit Dm.

- Lofi and Berné (2008) interpreted these discontinuities as paleo-submarine canyons that pre-date the initiation of the Messinian drawdown phase. Only the upper part of unit Dm (characterized by a chaotic high-amplitude seismic facies) is attributed to Messinian detritital deposits. Nevertheless, the volume of these chaotic deposits, estimated at around 1500 km^3 (with an average velocity of 2000 m/s) or 3000 km^3 (with 4000 m/s) by the same authors (Lofi et al., 2005) is far less than the estimated volume of eroded material in the entire Rhône Valley and Gulf of Lions shelf (~10 000 km^3).
- On the contrary, we suggest that all of unit Dm is Messinian and that the major unconformity observed at its base should be linked to the beginning of the main Messinian drawdown of the Mediterranean Sea (Bache, 2008). The full unit Dm, which has a volume of the same order of magnitude as the estimated volume of eroded material, is a probable candidate for the detrital deposits from the Messinian erosion. Several other considerations support our interpretation:

6.1.1 Pre-Messinian vs Messinian fluctuations of sea level

The main Messinian drawdown is the most prominent such event to occur in the Mediterranean and probably in the world. The consequences of this drawdown had dramatic effect leading to abnormal amounts of erosion in the Rhône Valley and sediment transfer into the basin. Numerous sea-level fluctuations occurred before the period of the Messinian drawdown (Haq et al., 1987) but none of them are comparable (100-200 m at the maximum).

The lower part of Unit Dm (Dm0 and the base of Dm1, the greatest in volume) correlates with LU0 (Fig. 3c). The Dm0-LU0 depositional sequences are genetically related sediments bounded by unconformity (base Dm0) and their correlative conformity (base of LU0). This phase therefore corresponds to a major sediment transfer, which built detrital wedges of thickness as much as 1000 m at the outlet of the Messinian rivers, and in the order of 800 m in the basin. A Messinian origin for only the upper part of unit Dm (characterized by a chaotic high-amplitude seismic facies) would mean that the erosive base of unit Dm (which is a regional major erosional surface that truncates the Miocene shelf) is not connected to the all important Messinian event but to a previous event. In this scenario the Messinian event would thus have produced less prominent unconformities (within the unit Dm) whereas the major regional erosional surface would have been produced by a previous event of lesser severity. To us this scenario seems unlikely. Instead, the most likely interpretation in the context of the regional distribution of unit Dm and its erosive base is that it is a product of the major Messinian drawdown. The surface resulting from this major drawdown would have overshadowed all previous events. In the case in the Provence Basin this is certainly true where the MES sometimes erodes up to the substratum.

6.1.2 Position of the unit Dm

The mapping of unit Dm and its basal erosional surface identified three subunits at the outlet of Rhône and Roussillon-Languedoc Messinian paleo-rivers (Fig. 4). The MES represents this preserved subearial landscape just before the Zanclean refilling of the basin, i.e., the terminal Messinian exposed landscape. The first unit (Dm0) is principally located at the outlet of the Rhône network. The others (Dm1, Dm2) are also located at the outlet of Roussillon-Languedoc network. These locations can be explained by a drawdown so extensive that he first impacted the Rhône Valley (Dm0) and then the Gulf of Lions shelf (Dm1-Dm2) with the Roussillon-Languedoc rivers that became a major source of sediment supply (Figs. 9 and 10).

Thus, seismic sequence geometries are consistent with a Messinian age for unit Dm and therefore we favor to attribute the major unconformity at its base to the onset of the major Messinian drawdown. Nevertheless, we do not rule out the occurrence of smaller erosional events (prior to the main Messinian drawdown) which may not have been preserved on the

Messinian shelf edge; i.e., in the transitional domain. This interpretation have strong implications on the Messinian Salinity Crisis scenario.

6.2 The Messinian scenario as viewed from the "central" basin

We must emphasize that the two-step scenario of the MSC proposed by Clauzon et al. (1996) is now widely recognized as the valid one by the respective authors of the Mediterranean-scale MSC scenarios mostly discussed during the last years, as illustrated by the “Consensus report” recently published (CIESM, 2008). We illustrate our interpretation of the Messinian evolution of the Provence Basin in Figures 9 and 10. Following an initial and limited Messinian regression (Clauzon et al., 1996) (Figs 9a and 10a), we recognize four major phases as described below.

The first phase is marked by a major detrital event, underlying the lowermost evaporite (LU1), and related to the major Messinian drop in the Mediterranean sea level (yellow areas in Figures 9b and 10b). This pre-evaporite step implies that thick evaporites in the central basin (visible at the seismic resolution) deposited after the subaerial exposition of the Gulf of Lions, certainly under low bathymetry. Loget et al. (2005) have shown that consecutive intense regressive erosion developed inevitably in the Gibraltar area. It should be a likely process to explain a continuous input of marine waters necessary to precipitate enough evaporites in the desiccated Mediterranean Basin. The assumption that central basin evaporites partly deposited under a high bathymetry and before the major phase of erosion (Krijgsman et al., 1999; Meijer and Krijgsman, 2005; Krijgsman and Meijer, 2008; Govers, 2009; Govers et al., 2009) should imply the observation of a major detritic event above evaporites in the basin. Such a depositional geometry has not been observed.

The second phase (Figs. 9c and 10c) corresponds to a strong change in the sedimentary regime as shown by the onlaps of the sediments during this phase (LU1) onto the underlying detritic layer. Sedimentation evolves from the first detrital event (phase 1) to a massive salt deposition (at the top of LU1 unit) resulting from an increase of salt concentration and continuous input of marine waters within the almost desiccated basin. The corresponding seismic facies is comparable to that of the Upper Evaporites facies comprising of halites, gypsum, anhydrite, lacustrine mud and marls with clastics reworked from the margin. Therefore, we attributed LU1 to the onset of evaporite/detrital deposition in the central Provence Basin. These “Lower Evaporites” present a thickness of ~1500 m, much higher than what was assumed previously (500 to 600 m) (Montadert et al., 1978; Lofi et al., 2005). Such a thickness of Lower Evaporites must be tested in future quantitative studies of the Messinian Salinity Crisis.

The third and the fourth phases correspond to a two-step trangression at the end of the crisis. An initial relatively slow sea level rise (Figs 9d and 10d) permitted the development of a transgressive surface with smooth topography (light blue line) identified previously on seismic profiles. These flatten the top of regressive prisms (Dm0, Dm1, Dm2) and represent the limit between Messinian and Pliocene deposits (Fig. 6). During this relatively slow landward migration of the Messinian shoreline, the continuous action of waves and tides smoothed the reliefs of the Messinian erosional surface. This interpretation is supported by the presence of 50 m of azoic sand at the top of the evaporites in the GLP2. This unit, described by Gorini (1993), could correspond to the transgressive sand from the upstream marine abrasion by wave ravinement. The fourth phase corresponds to the Zanclean rapid reflooding (Hsü et al., 1973a; Clauzon and Cravatte, 1985; Pierre et al., 1998; Blanc, 2002; Lofi et al., 2005) and has been precisely dated at 5.332 Ma (Hilgen and Langereis, 1993; Van

Couvering et al., 2000; Lourens et al., 2004). It is clearly marked by the transition between two morphologies (rough and smooth), at a constant two-way traveltime/depth of 1.6 seconds over the entire shelf (Fig. 6). Up to this two-way traveltime depth, the irregular 'rough' or badland topography (of MES) illustrates the Messinian paleogeography as it was at the end of the Messinian erosional period (Figs. 9d and 10d, in dark blue). This rapid reflooding implies a cessation of the action of waves, which has preserved badland morphologies (Fig. 10e). The change in morphology corresponds therefore to the transition between a subaerial erosion (rough morphology) and a submarine erosion (smooth morphology). In this scenario, the 1.6 second limit corresponds to the position of the paleoshoreline at 5.332 Ma and is an appropriate marker for subsidence studies.

7 Conclusion

Our results support the deep-desiccated evaporite basin hypothesis (Hsü et al., 1973a): thick detrital deposits at the outlet of the Messinian Rhône and Messinian Languedocian and Pyrenean rivers are, as would be expected (Ryan and Cita, 1978; Clauzon, 1982), present at the transition between the Miocene shelf and basin. On the basis of depositional geometries, studied for the first time over the entire margin and down to the central basin of the Western Mediterranean, we are able to underscore the following points:

- the evidence of a pre-evaporite phase corresponding to a prominent erosional crisis responding to a major drawdown of the Mediterranean seawater. Assuming than this major drawdown corresponds to the major Messinian drawdown, we can conclude that the Mediterranean bathymetry significantly decreased before the precipitation of central basins evaporites. A deep water formation seem unlikely.
- the presence of a thick probable "Lower Evaporites" series (with a thickness up to 1500 m) located below the salt sequence. This implies that the total thickness of Messinian deposits in the basin should as much as 3500 m (including the pre-evaporite

phase and the salt). This thickness also implies that the relief from shelf to basin floor was already significant at the time of their deposition. The basin was gradually filled during the Messinian Salinity Crisis. This infilling would have had a significant effect on the vertical movements of the basin.

- the characteristics of the final discontinuity surface and of two types of morphology (rough and smooth) provides evidence of the basin being resubmerged at the end of the Messinian Crisis. This refilling was first moderate accompanied by transgressive ravinement and later rapid so as to “preserve” the paleoshoreline at 5.332 My and the Margin Erosion Surface. These markers of a two-step reflooding observed in the Gulf of Lions provide remarkable points of reference for subsidence studies. It will be necessary to correlate them at the scale of the whole Western Mediterranean, as well as within the Eastern basin.

Several authors have tried to study the subsidence in the Provence Basin and the isostatic readjustments related to the Messinian Crisis (Ryan, 1976; Steckler and Watts, 1980; Burrus and Audebert, 1990; Meijer and Krijgsman, 2005; Krijgsman and Meijer, 2008; Govers, 2009; Govers et al., 2009). The view that we outline provides new fodder for the study of subsidence of the Provence Basin and better understanding its structural evolution. An other interesting perspective of this work could be the study of the lithospheric response to strong and rapid variations of weight during the Messinian Erosional and Salinity crises.

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10 Figure Captions

Figure 1: Location of the Messinian evaporite series (halite and other evaporites) in the Western Mediterranean (modified for the Gulf of Lions from Montadert et al., 1978 and Rouchy and Caruso, 2006) and the area drained by the Messinian rivers in Southeastern France (hatchured). The Late Miocene Betic and Rifian corridors (dotted line) are taken from Martin et al, 2001. The study area is outlined in black.

Figure 2: Seismic data and boreholes used for this study. The bold lines represent the location of the line drawings in Figure 3.

Figure 3: Line drawings perpendicular and parallel to the margin of the Gulf of Lions (locations shown in Figure 2). The Messinian crisis is recorded distinctly in three domains illustrated on profiles a, b and c basinward from the coast: an eroded domain, an intermediate domain and an evaporite accumulation domain. These domains are crossed by profiles d, e and f respectively. The eroded domain corresponds to the Miocene shelf with a 'rough' subaerial erosion surface (in blue). The intermediate domain is characterized by the presence of a sedimentary unit (unit Dm) that shows up well on Profile b. The unit is bounded at its base by an erosion surface (in red) that truncates the Miocene slope, and at its top by a 'smooth' erosion surface (in pale blue) that truncates unit Dm (characteristic of the intermediate domain) and the Miocene shelf at the end of the Messinian time. The deep basin is characterized by the presence of salt (MU, transparent seismic facies) with underlying reflectors (LU1). The reflectors are continuous, high amplitude, and clearly onlap Unit Dm.

Figure 4: Map showing the sedimentary units and the erosion located just below the Pliocene. The drainage network (Margin Erosion Surface) dominates on the shelf. The 'rough-smooth'

erosion boundary is in pale blue. Below the smooth erosional surface, one can see the extension of unit Dm. The evaporite domain transgresses this intermediate domain.

Figure 5: Detail of the transition from the eroded domain (a, b) to the intermediate domain (c, d, e, f, g, h, i) on the Languedoc side. In the eroded domain, the 'rough' subaerial erosion surface separates the Miocene shelf from the Pliocene units. In the intermediate domain, Unit Dm occurs inserted between the Miocene series and the Pliocene series. We thus find erosion in the first domain and a more complex history in the intermediate domain, which shows an initial episode characterized by a major discontinuity (at the base of Unit Dm), although it is difficult to determine down to which point subaerial erosion was active.

Figure 6: Detail of the transition from the 'rough' erosion surface (Margin Erosion Surface) to the 'smooth' erosional surface. The 'rough-smooth' boundary is located at a constant two-way traveltime depth of 1.6 seconds over the entire margin (a, b, c, d). Near the Pyrenees, the 'rough-smooth' boundary is located around a two-way traveltime depth of 1.4 seconds (e, f).

Figure 7: Estimated thickness of Miocene sediments eroded during the Messinian Event.
A: The continuity and parallelism of the Miocene series (aggradation) under the Messinian erosion surface make it possible to estimate the eroded thickness. The estimation was made by projecting a reference Miocene reflector onto the last seismically observable Miocene layer.
B: Isopach map of the eroded thickness. This thickness could only be estimated in the area where the reference Miocene reflector was still visible. The thickness of sediments eroded in the areas where the substratum is directly affected (Rhône side) is not taken into account. The significant, but minimum, estimated volume (more than 4000 km^3 and probably around 10

000 km^3) is to be compared with the volume of unit Dm located downstream in the intermediate domain.

Figure 8: Estimate of the volume of unit Dm deposited in the intermediate domain. One should note that this volume (9400 km^3) is of the same order of magnitude as the eroded volume (around 10000 km^3). Unit Dm is thus the only unit that corresponds to the volume eroded upstream.

Figure 9: Paleogeographic synthesis of the observations made over the entire Gulf of Lions margin arranged in chronological order.

A: Reconstruction of the Miocene margin before the major Messinian drawdown. The Miocene sea drowned part of the Rhône Valley. The Miocene coastline in the Rhône Valley is taken from Besson et al. (2005). The shelf ended as onlaps on the basin edges, where the substratum was in a higher position. Minor erosions related to previous minor drawdowns can be assumed.

B: The drop in the Mediterranean sea level gave rise to subaerial erosion on the shelf (Margin Erosion Surface). Downstream, a submarine erosion surface (base of unit Dm) across which the first detrital deposits (turbidites?) transited.

C1: The sea-level drop continues to its lowest level. The Messinian rivers carry large amounts of sediment from the Miocene shelf toward the intermediate domain. This sedimentary transfer brought about basinal subsidence and a readjustment of the shelf lightened by erosion. Within the basin, a supply of seawater concentrated with salt, plus evaporation, led to the precipitation of evaporites which would onlap unit Dm and fill the available space created by the subsidence. Where the substratum is steep, as in Provence or on the Catalonian margin, the detrital series are thin and the basin evaporite series directly onlap the substratum.

Isostatic readjustment could have been the cause of the fracturing seen within the Miocene shelf series.

C2: The sea level is still at its lowest level. Salt precipitates at the height of the Crisis.

D: The morphology of the 'smooth' erosion surface present in the intermediate domain suggests transgression of the coastline. This transgression would bring about abrasion of the underlying series up to the 'rough-smooth' boundary. The 'smooth' surface is thus interpreted as a marine ravinement surface. The Upper Evaporites would be related to a change in the basin's salinity conditions (Lago Mare?).

Figure 10: Synthetic cross section of the observations made over the entire Gulf of Lions arranged in chronological order. See Figure 9 for section locations and explanations.

Figure1
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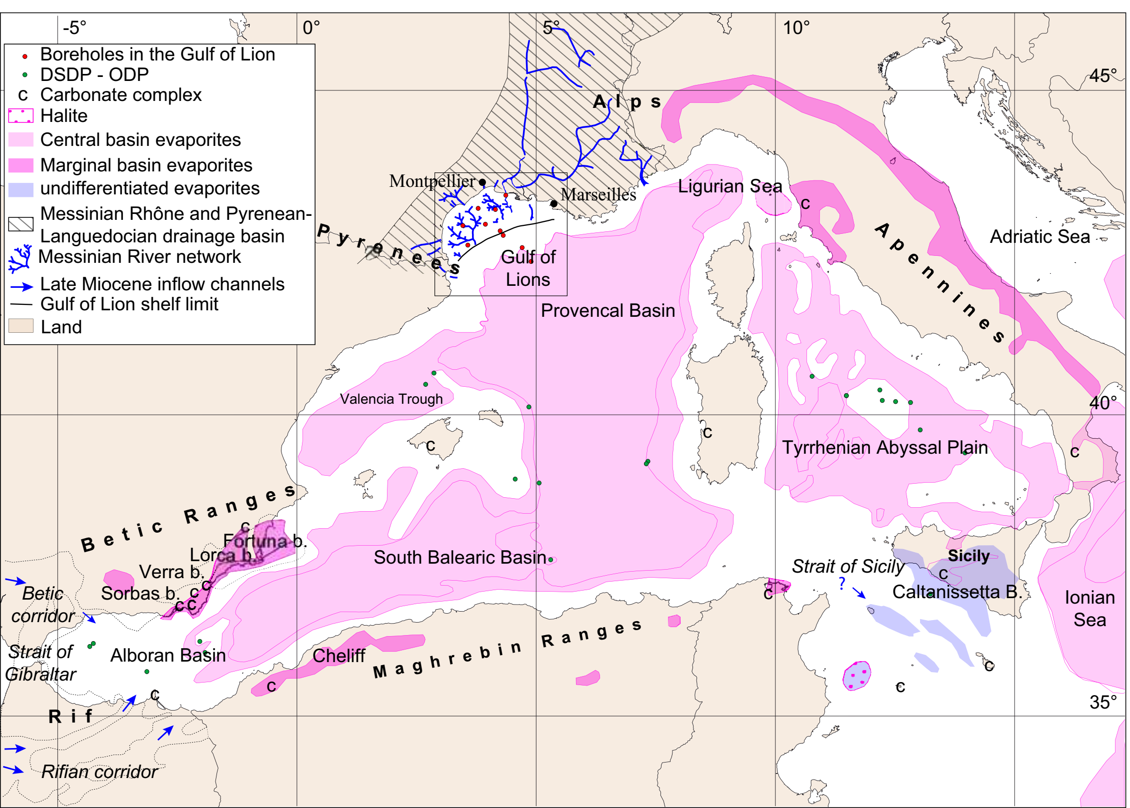

Figure2
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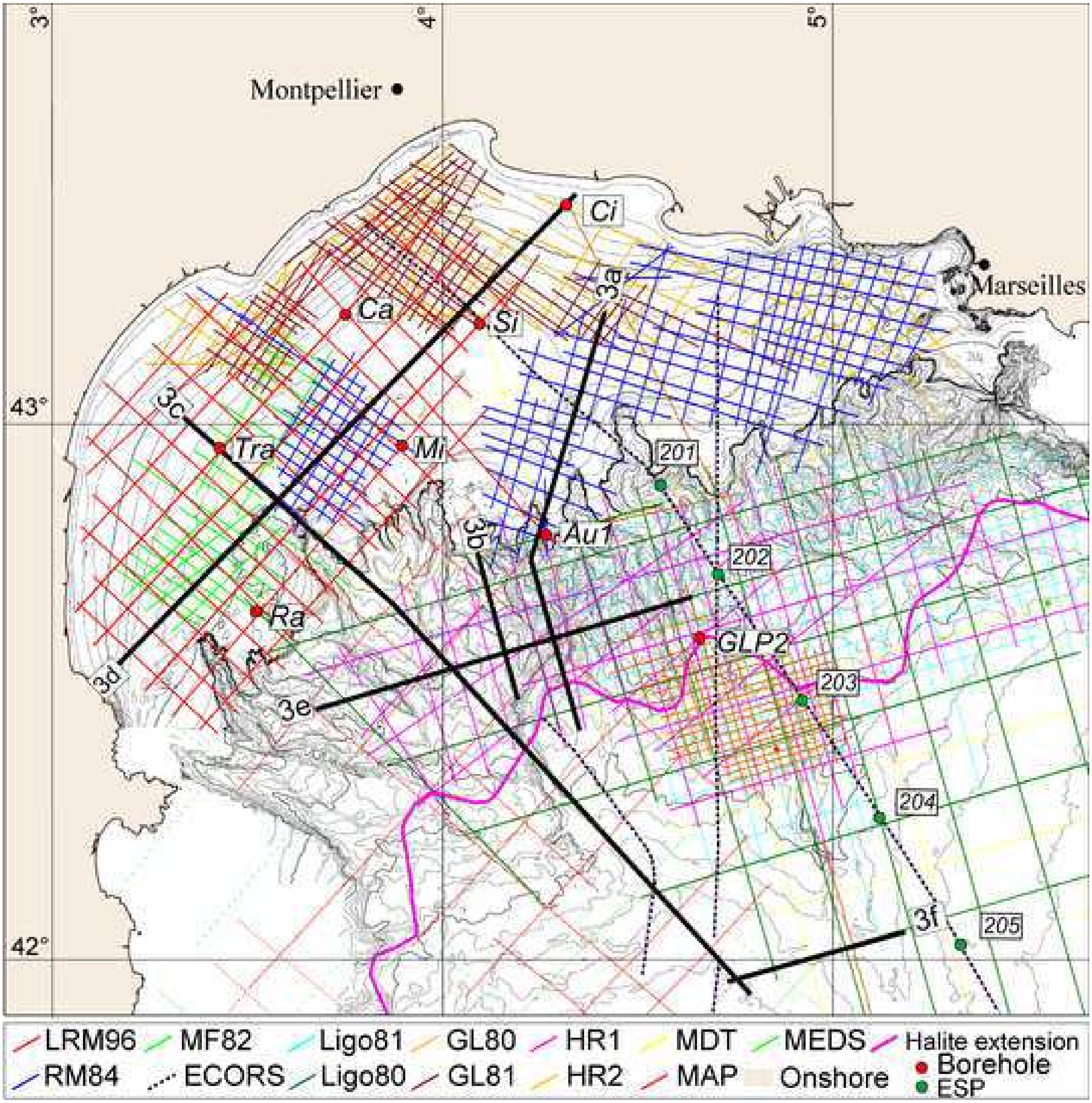

Figure3

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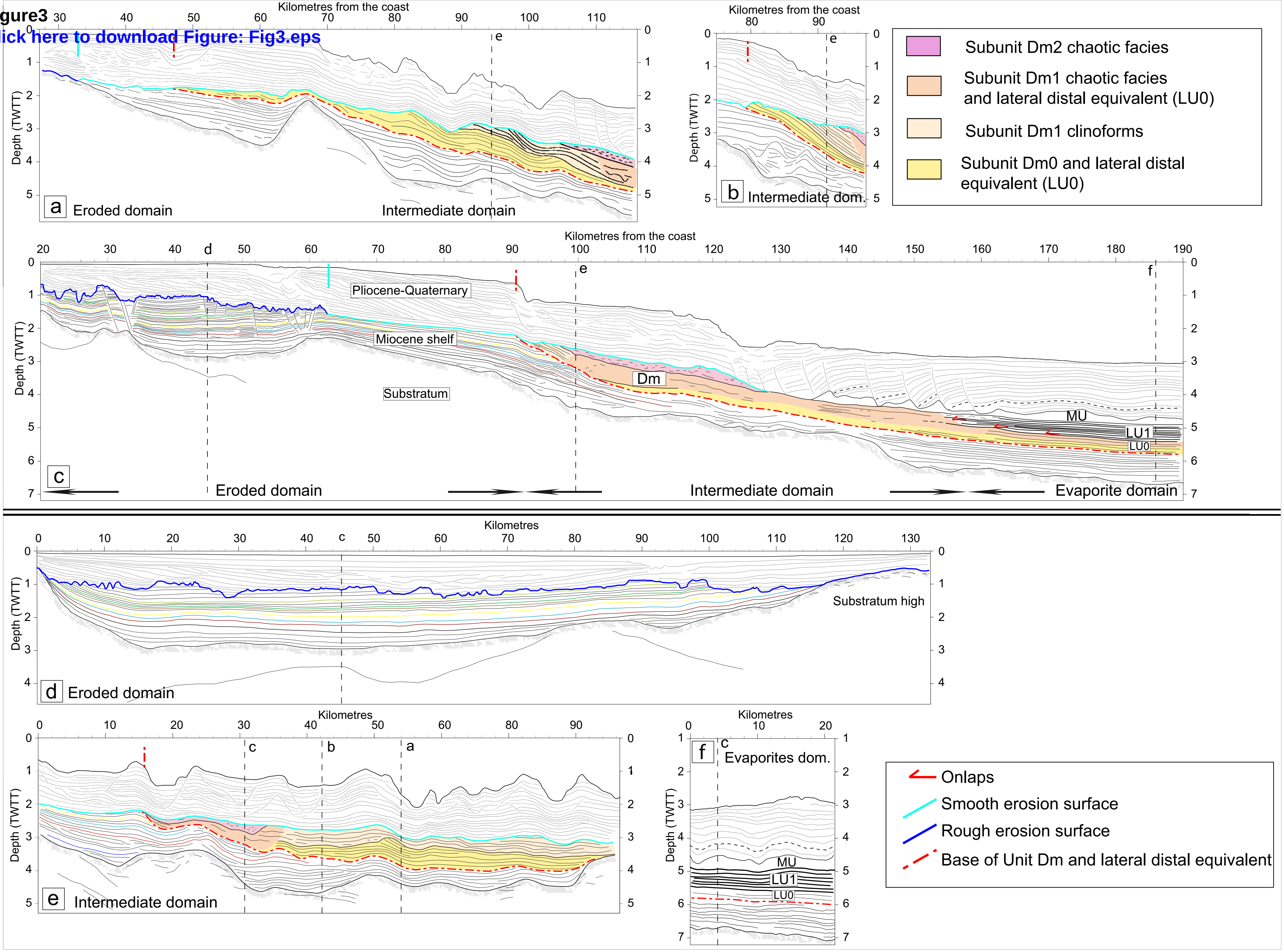

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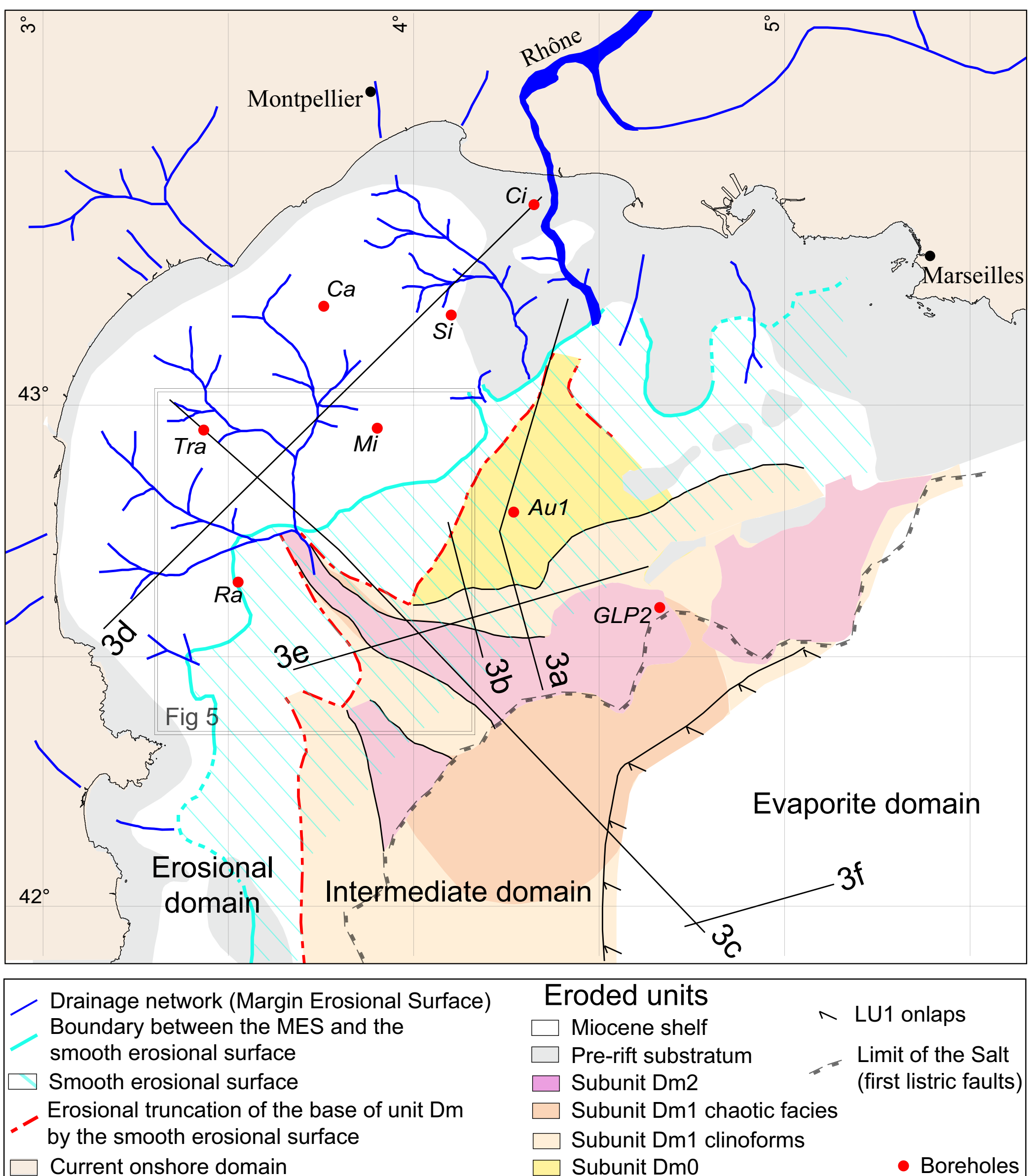

Figure5

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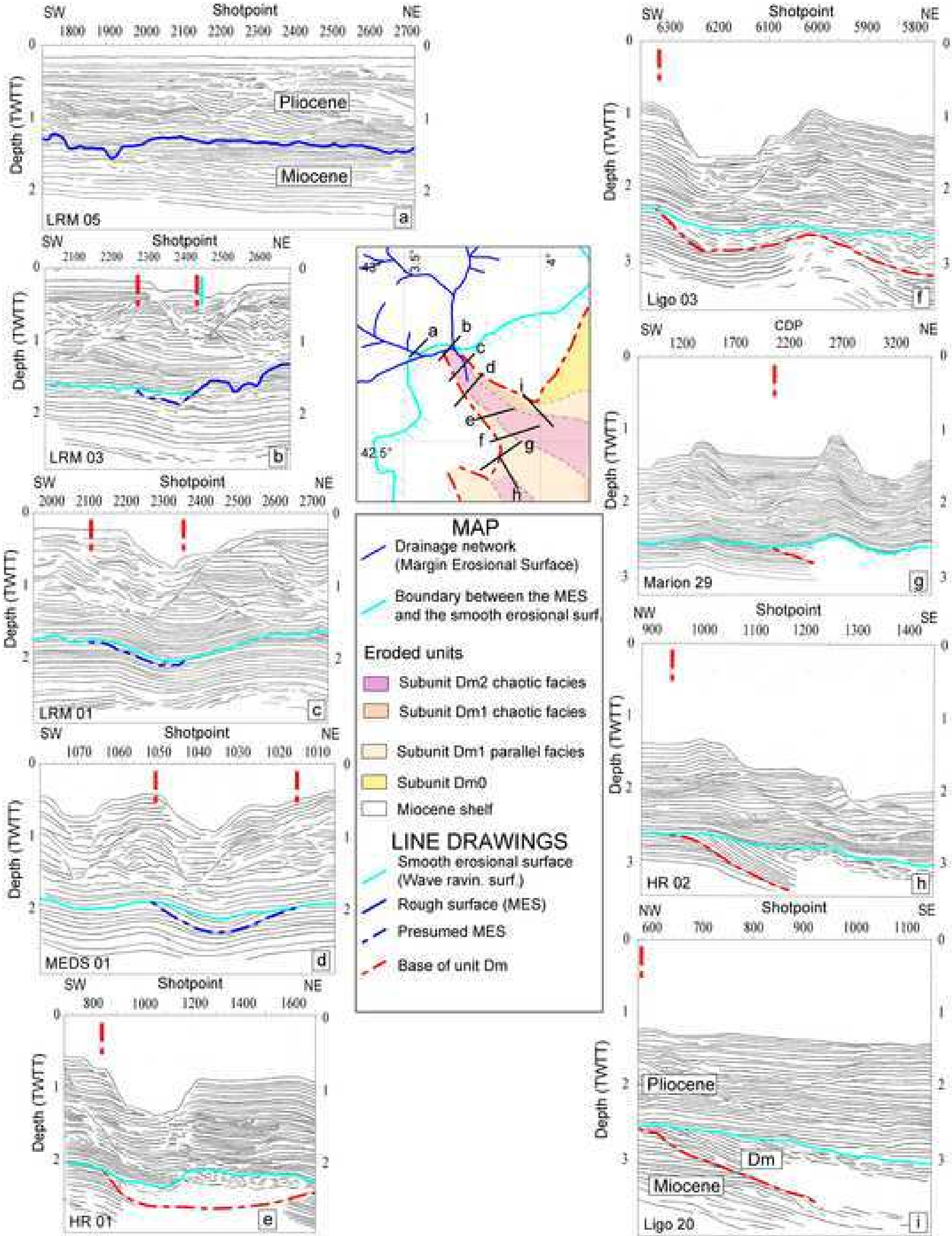

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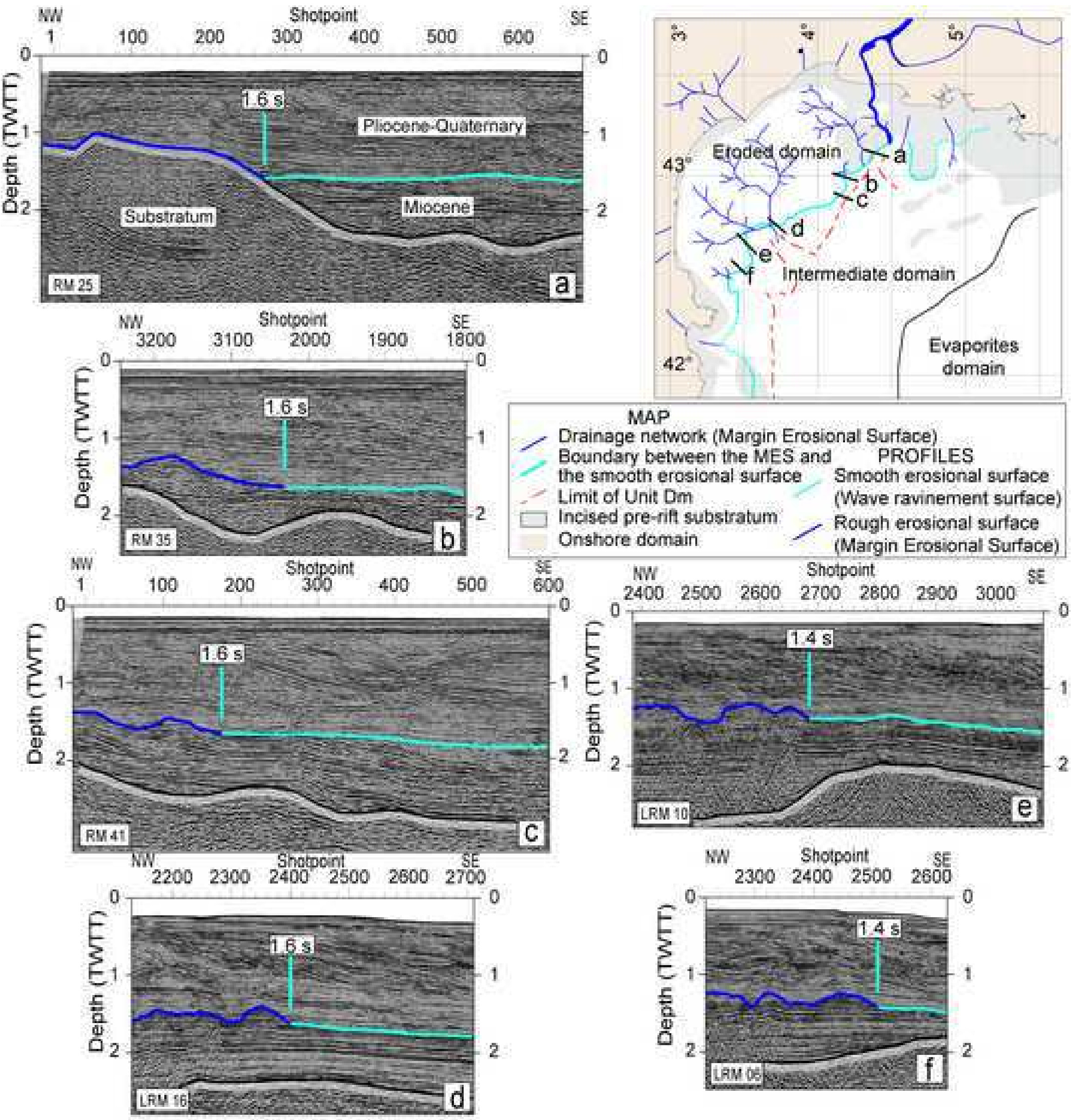

Figure7

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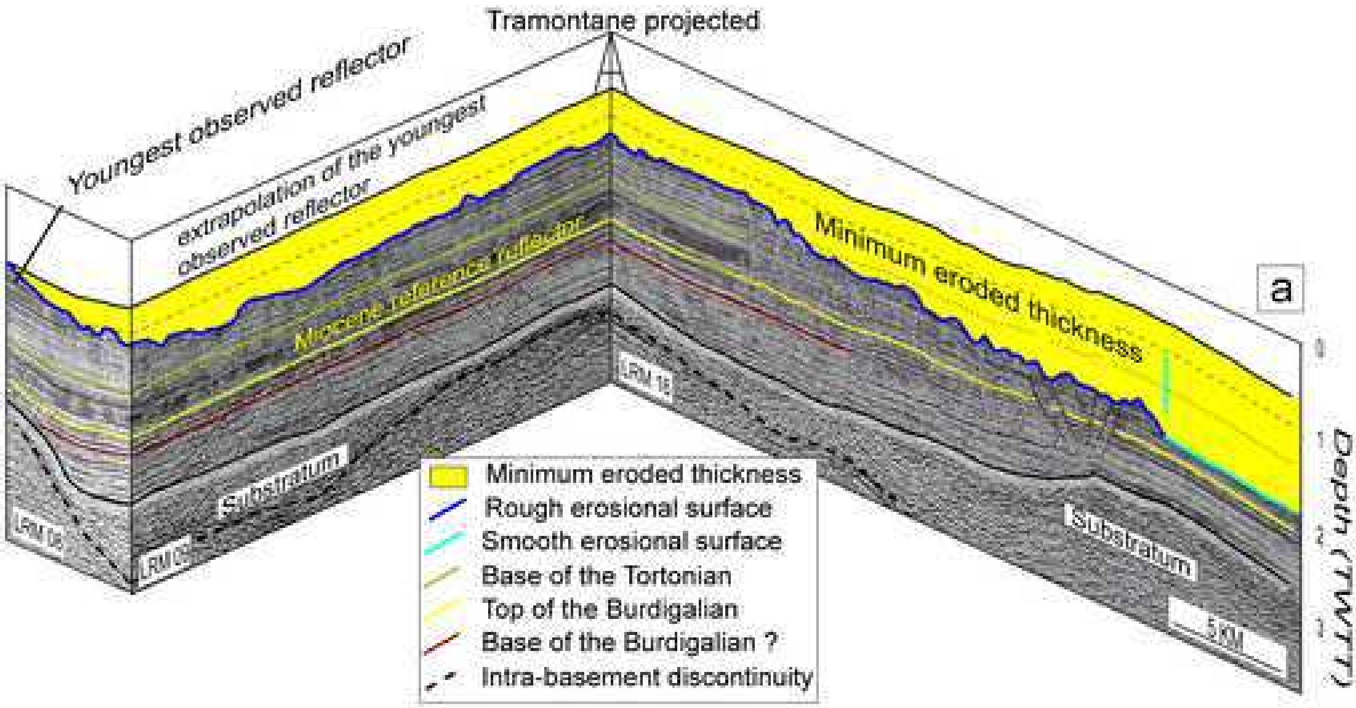

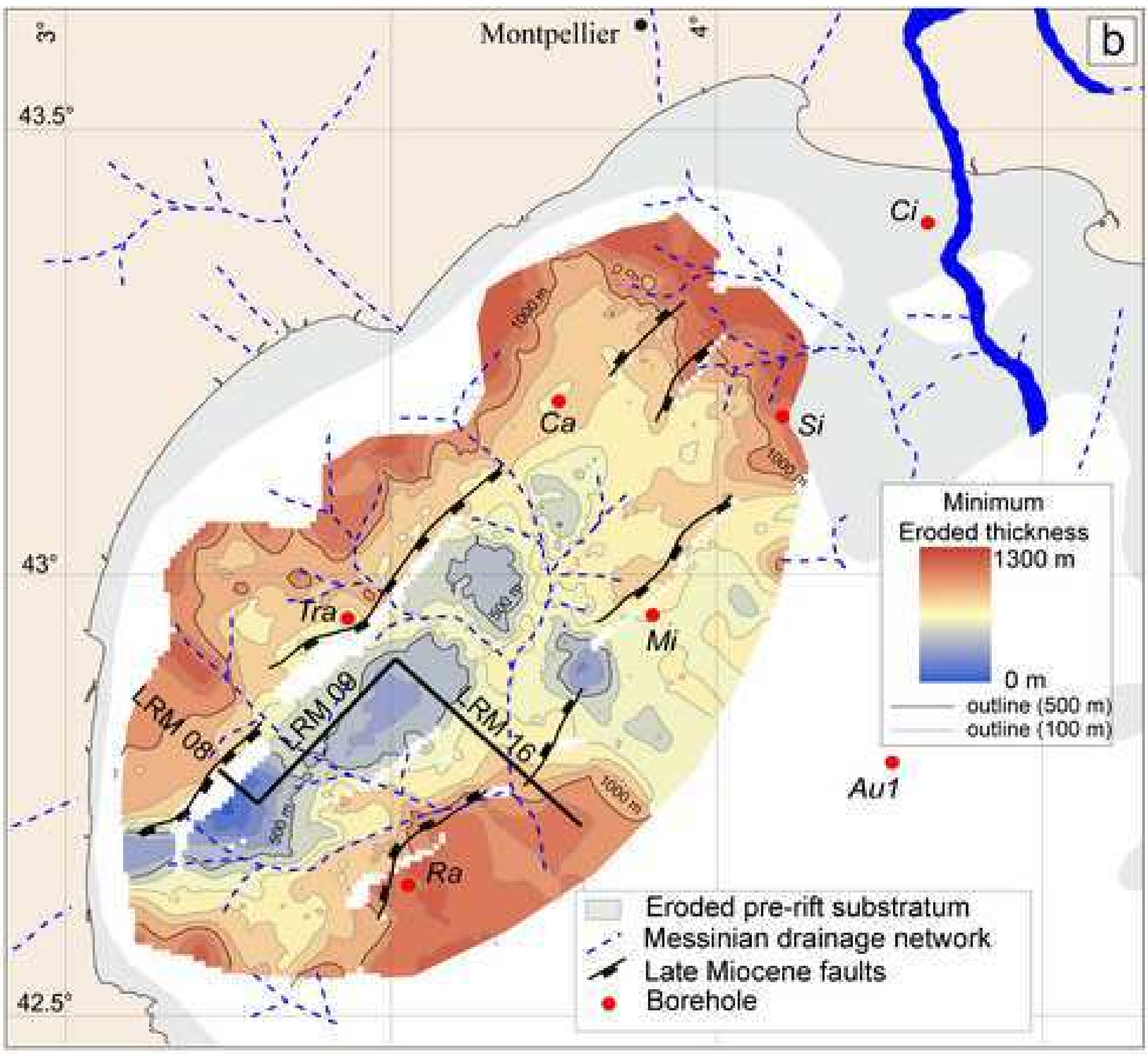

Figure8

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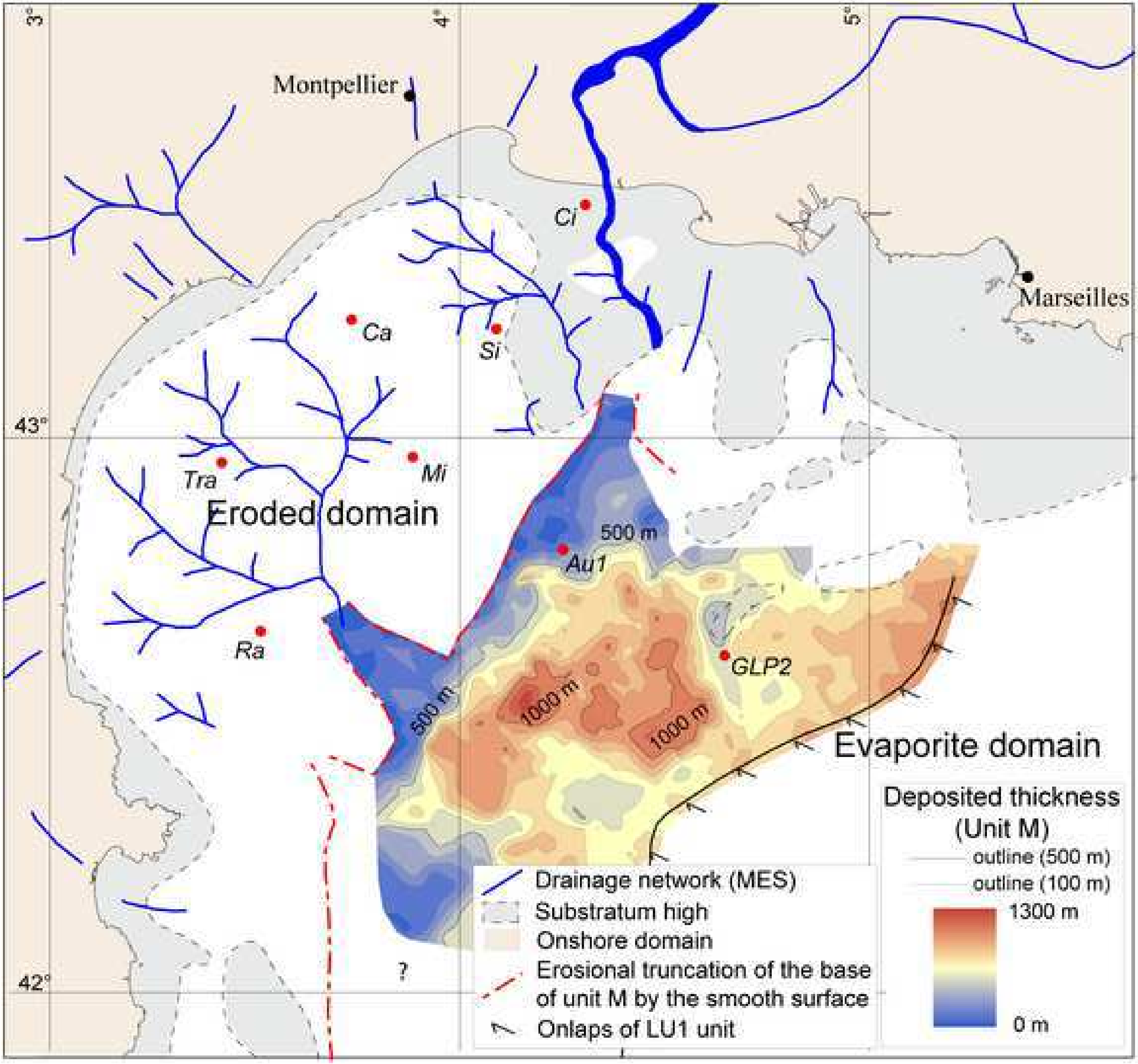

Figure9

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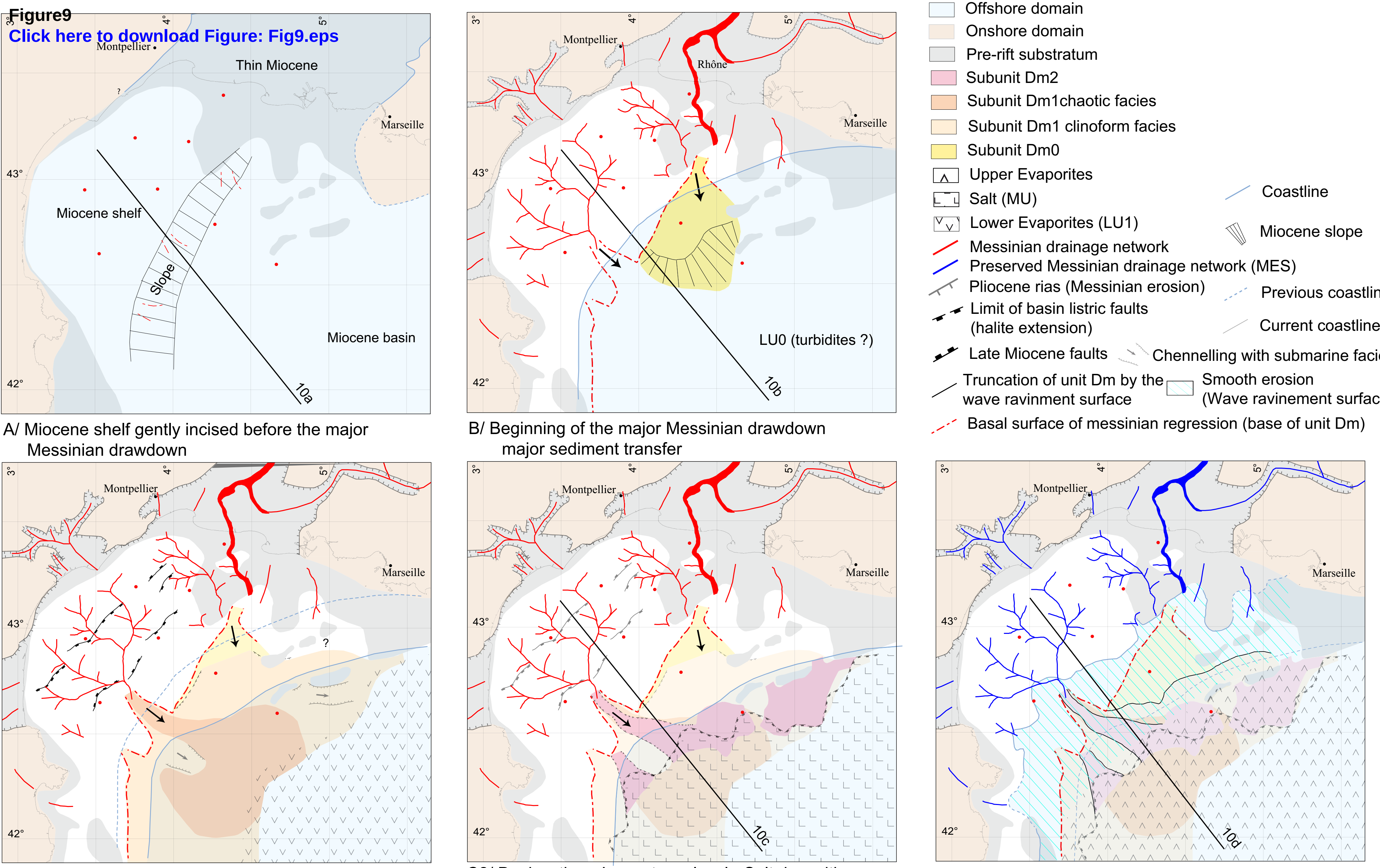

A/ Miocene shelf gently incised before the major Messinian drawdown

B/ Beginning of the major Messinian drawdown major sediment transfer

C1/ Beginning of desiccation - Low sea level

C2/ Desiccation - Lowest sea level - Salt deposition

D/ Rise of sea level accompagnied by smooth erosion

Figure10

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